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AIAA 99-2190

Design and Test Results of an Advanced Liquid Hydrogen Turbopump

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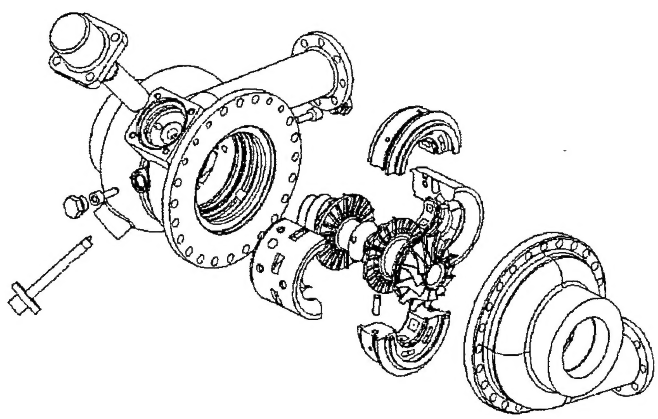

35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
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Los Angeles, California

ABSTRACT

This paper discusses the design, the test facility, and the test results of an Advanced Liquid Hydrogen Turbopump for a 50,000 pound (22,679 kg) thrust Upper Stage Expander Cycle Engine being developed by Pratt & Whitney Liquid Space Propulsion under contract for the United States Air Force Research Laboratory (AFRL) to support the Integrated High Payoff Rocket Technology (IHPRPT) program. The Advanced Liquid Hydrogen Turbopump is designed to provide improved system thrust to weight, decreased hardware/support costs, and increased reliability. These benefits will be accomplished and demonstrated through design, development, and test of this high speed, high efficiency, two stage hydrogen turbopump capable of supplying 16 lbm/sec (7.3 kg/sec.) of liquid hydrogen at 4600 psia (323.4 kg/cm^2).

INTRODUCTION

The Air Force, Army, Navy, and NASA have implemented a three phase, 15-year rocket propulsion technology improvement effort to "double rocket propulsion technology by the year 2010". This initiative, designated the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) established performance, reliability, and cost improvement goals for each of the three phases. These goals are to be met by advancing component technology levels through design, development, and demonstration, followed by an integrated system level demonstrator to validate performance to the IHPRPT system level goals. Pratt & Whitney Liquid Space Propulsion, under contract to the United States Air Force Research Laboratory ~~(contract F04611-94-C-0008~~ – design and ~~F04611-97-C-0029~~ test), has developed and tested an Advanced Liquid Hydrogen (ALH) turbopump. This turbopump is designed to support the IHPRPT LOX/LH2 boost/orbit transfer propulsion area Phase I goals. These system level goals include; a 1% improvement in vacuum specific impulse, a 30% improvement in thrust to weight, a 15% reduction in hardware/support costs, and a 25% improvement in reliability relative to current state-of-the-art levels.

under design & test contracts

Pratt & Whitney, in cooperation with the United States Air Force Research Laboratory, established an advanced upper stage expander engine computer model for the purpose of establishing the individual component requirements necessary to ensure the IHPRPT Phase I system level goals are achieved. This cycle model was used to establish the performance, cost, weight, and thermodynamic operating requirements of the ALH turbopump.

DISCUSSION

As stated above, an advanced expander engine model, which met the IHPRPT Phase I system level goals was established, from which component goals could be determined. Since Pratt & Whitney has extensive history with the RL10A-3-3A, ~~which is also the baseline for the IHPRPT goals~~, it was used as our starting point for developing the advanced expander engine cycle. The RL10A-3-3A has 16,500 pound (7484 kg) vacuum thrust, specific impulse of 442.5 seconds, and a thrust to weight ratio of 53. It utilizes a two stage turbine driven by the expanded hydrogen from the combustor and nozzle cooling tubes. The RL10 turbine drives both the two stage hydrogen turbopump and, through a gearbox, the single stage Liquid Oxygen (LOX) turbopump. The maximum cycle pressure is approximately 1100 psia (77.33 kg/cm^2) with a chamber pressure of 470 psia (33 kg/cm^2). The expander cycle developed for the RL10 is used in each member of the RL10 family, covering the 16,500 to 24,750 pound (7484 - 11226 kg) thrust range. The advanced expander engine cycle, established to support the IHPRPT Phase I goals, will allow further growth to 50,000 - 80,000 pounds (22,679 - 36,287 kg) while maintaining the benefits of the RL10 family history.

remove

WORDS PROCEEDING ADVANCED

The growth potential of the current RL10 family is limited by the fuel pump discharge pressure which is in turn limited by the heat pickup capacity of the combustor and nozzle cooling tubes. Until recently no significant improvement in thermal conductivity was available without an unacceptable sacrifice of material properties. This problem has been solved by using PWA 1177 dispersion strengthened copper in the Advanced Expander Combustor (AEC) being developed for the AFRL ~~on~~ UNDER contract ~~F04611-95-C-0123.~~

The additional heat load capacity provided by the AEC supports an increase in turbopump discharge pressure, allowing an increase in chamber pressure. Analysis of

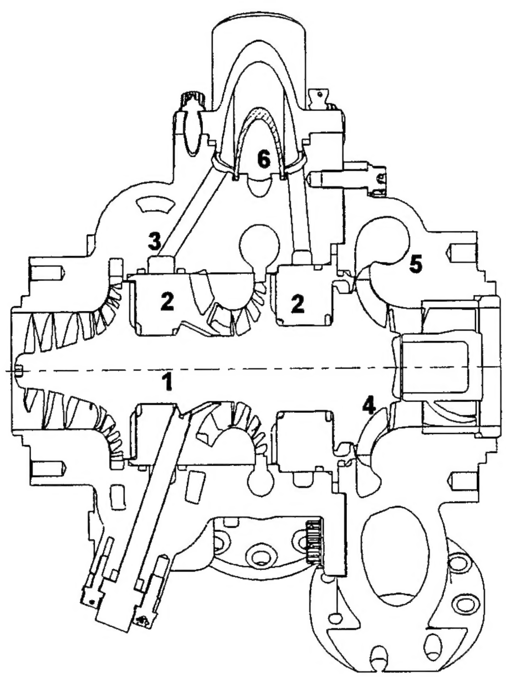
an expander cycle with the improved heat load capacity supports a stable expander cycle operating at a chamber pressure of 1375 psia (96.7 kg/cm2) with a maximum cycle pressure of 4600 psia (323.4 kg/cm2) at the ALH fuel turbopump discharge. The final system balance provided a heat load capacity of 22,833 Btu/sec (24M N-M/sec) available to drive both the ALH fuel turbopump and the LOX turbopump with margin remaining for roll control thrusters, boost pump drive, or equivalent bypass requirements.

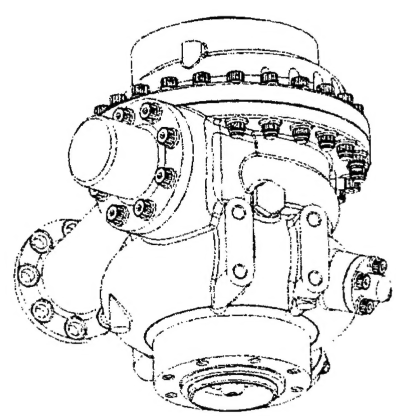
An advanced expander engine cycle (Ref. AIAA 99-2599, Design and Development of a 50K LOX/Hydrogen Upper Stage Demonstrator) was configured to meet IHPRPT Phase I goals. Once the advanced expander cycle model was established, the performance and thermodynamic operating requirements of the individual components could be isolated from the system level characteristics to establish the design requirements of the ALH.

ALH TURBOPUMP DESIGN

The following is a summary of the ALH turbopump design with a more detailed description in AIAA 98-3681, Design and Development of an Advanced Liquid Hydrogen Turbopump.

The ALH turbopump design goals maximize pump discharge pressure while minimizing turbopump weight and production cost. The combination of high pump discharge pressure and low turbopump weight requires maximum rotor speeds to attain high impeller tip speeds at a minimum impeller diameter. Rotor speed has typically been limited by conventional bearing DN limits. The high leverage-enabling design feature of the ALH turbopump is the fluid film rotor support system. The ALH turbopump has been designed with a pressurized fluid film rotor support system to provide;: high radial and axial stiffness, low cross coupled stiffness, optimized hydrodynamic and rotordynamic operation, accurate rotor position control, with minimized rotor stresses, bearing loads, and operating clearances. Additionally, the use of fluid film bearings drastically reduces the turbopump part count, directly reducing costs and improving reliability. The ALH turbopump is shown in cross section in Figure 1.





Major Features:

1 One piece titanium rotor.
2 Split hydrostatic bearings.
3 Cast pump housing with integral crossover passages.
4 Radial inflow turbine.
5 Cast turbine housing with vaneless inlet volute.
6 Filtered bearing supply.

Figure 1. Cross section & External View of ALH Turbopump

Rotor Support System

Fluid film bearings are a key technology in developing long life, dependable rocket turbopumps. In contrast to rolling element bearings, the shaft and bearing do not come in contact once normal operation is achieved. Life limitations due to steady state wear of rotating components, found in rolling element bearings, are eliminated. The reduction in part count, roughly an order of magnitude, increases the component and overall system reliability and reduces complexity. The high levels of stiffness and damping found in fluid film bearings eliminate the need for additional damping devices, such as damper seals. System efficiency is also increased by employing a combination of radial and thrust bearings, thereby minimizing rotor excursions and maintaining reduced blade tip clearances.

Rotor axial thrust loads will be transferred to the static structure through a pressurized fluid film thrust bearing. This bearing is an integral part of the pump housing and is two-sided to provide precise rotor positioning and stability. One side of the bearing interacts with a small land on the back face of the second stage pump impeller; the other side interacts with the back face of the turbine rotor.

Start and stop cycles may produce momentary contact of the rotor bearing surfaces. It is only during these transient contacts that the hydrostatic and thrust bearings experience wear. The effects of wear in the ALH turbopump can be minimized by the selection of bearing surface materials. The bearings and mating rotors have fine surface finish and a combination of thin film hard coating on the rotor and sacrificial rub coatings on the static components provide low friction, wear resistant surfaces. This prevents degradation of the surfaces and/or galling associated with conventional bearings. Use of extremely thin film coatings maintains accurate rotor positioning even if the sacrificial stator coating is consumed.

Pump Design

The two stage ALH turbopump uses a high speed inducer and high stage-loaded impellers to achieve low pump weight, low cost, high power density, and high efficiency. The 174,240 rpm ALH turbopump impellers have tip speeds of 2281 ft/sec (695.3 m/sec), a per stage head rise of 74,128 ft (22594.3 meter), and an overall pump pressure rise of 4,500 psid (306 kg/cm^2). This value exceeds the current tip speed limit of approximately 2000 ft/sec (609.6 m/sec) for shrouded impellers. The first stage features an axial flow inlet and inducer, and a radial discharge unshrouded centrifugal impeller, to achieve good suction performance. The first stage impeller discharges into a vaneless diffuser, followed by a continuous passage internal crossover to diffuse and deswirl the flow before delivering it to the inlet of the second stage.

The second stage consists of another unshrouded centrifugal impeller similar to the first stage. The second stage impeller also discharges into a vaneless diffuser. The flow is then collected in a scroll-type, single discharge volute collector, followed by a conical diffuser. A secondary collector has been integrated into the primary collector flowpath to maximize the hydrostatic bearing and thrust bearing supply pressure.

Turbine Design

To meet the ALH turbopump design objectives, the turbine must achieve maximum performance while minimizing cost, size, and weight. The ALH turbine uses an advanced compact radial turbine to achieve a 13% increase in speed capability, a 10% improvement in turbine performance, and reduce turbine cost and weight. A toroidal inlet volute minimizes the circumferential static pressure and gas angle gradients entering the turbine rotor while minimizing the total pressure loss in the volute. This assures a volute with maximum performance with minimal impact on the turbopump shaft radial side loads.

The reduction in turbine radial side load was accomplished by using advanced computational fluid dynamics analyses to design the volute manifold flowpath to achieve a constant circumferential static pressure, thereby eliminating the side load on the rotor shaft. By configuring volutes using advanced design tools, the excess area incorporated in the constant area toroid is removed, reducing the housing weight by approximately 12 percent. By integrating the radial inflow turbine inlet volute designs, the need for an inlet guide vane is eliminated.

The ALH turbine was designed with reduced thru-flow velocities, increased reaction, and increased airfoil loading relative to previous expander turbines. The increased blade load reduces the airfoil count and provides a blade with a low aspect ratio and a high

degree of camber, assuring a stiff blade capable of high speed operation.

Mechanical Design

The mechanical design approach for the ALH turbopump has been to promote simplicity via low parts count. Low parts count has proven to improve maintainability, cost, and reliability, and reduce weight. Lower parts count also minimizes the dimensional tolerance stack-ups that are critical to turbopump performance and pressurized fluid film bearing operation. To minimize parts count the turbopump design uses a single piece rotor, two cast housings, and two split hydrostatic bearings for a total of only 5 primary parts (see Figure 1). The increased speed of the ALH allows the pump and turbine diameter to be reduced to approximately 3 inches (8 cm), with a shaft length of only 7 inches (18 cm). These improvements provide an Hp /Weight ratio of 141 for the ALH compared to 11 for the RL10 ~~baseline~~ A comparison of the ALH hardware to the RL10 ~~baseline~~ equivalent is displayed in Figure 2.

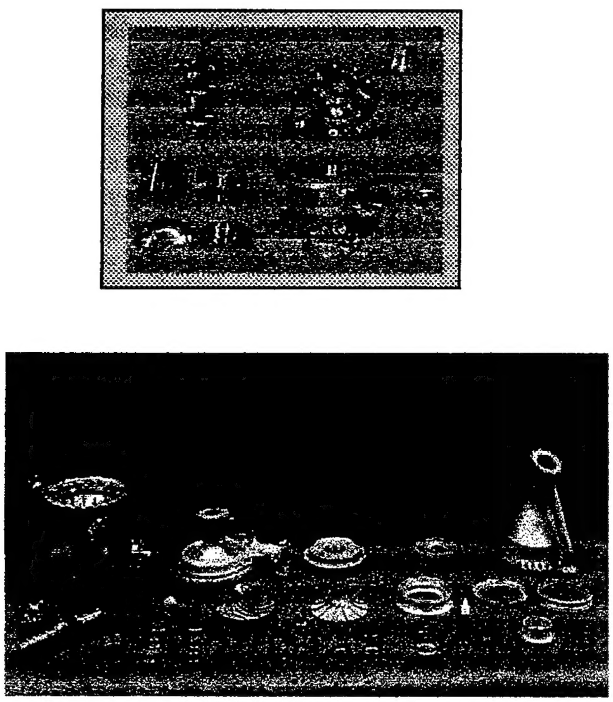


Figure 2. Comparison of ALH to RL10 Hydrogen Turbopumps

Advanced Rotor Sensor

Measurement of the rotor speed and position in turbomachinery is useful to support health monitoring, provide performance data and provide over-speed protection. The position sensing equipment included a new dual channel, capacitance sensor in the pump end of the turbopump and a single channel inductance sensor in the turbine end. The capacitance sensor monitored orthogonal surfaces on the rotor, which had three controlled slots machined into one surface and were used to establish rotor speed. This sensor consisted of two probes located 90 degrees apart circumferentially and was canted 30 degrees toward the pump inlet. From these two probes the rotor axial position, radial position, and speed were measured and recorded. An inductance probe, capable of measuring the rotor axial position and rotor speed, was added as a backup system and had the capability to measure rotor axial position as well as rotor speed from a series of controlled holes machined into the turbine disk.

ASSEMBLY

Assembly of the ALH was performed in the clean rooms and facilities used for assembly of the RL10 and SSME turbopumps. As illustrated in Figures 2 and 3, the parts count for the ALH is much lower than the RL10, or the SSME turbopumps. The assembly sequence for the ALH is rather simple due to the low parts count and attention to assembly requirements in the initial design effort. The ALH assembly process consists of 4 basic steps. 1) Position the bearings around the shaft. 2) Thermally size the pump housing. 3) Insert the rotor and bearing assembly into the pump housing. 4) Bolt the turbine housing to the pump housing. Through a disciplined development of the assembly process, the assembly time has been reduced to less than 4 hours for the ALH, compared to thousands of hours for the SSME turbopumps. Disassembly is a simple reversal of the assembly process, including the thermal sizing of the housing and takes approximately the same time as assembly. This demonstrated ability to turnaround the hardware validated both the design philosophy, to keep the parts count low, and the design process, to take assembly and manufacturing into account for the baseline design.

INTERESTING PAGINATION

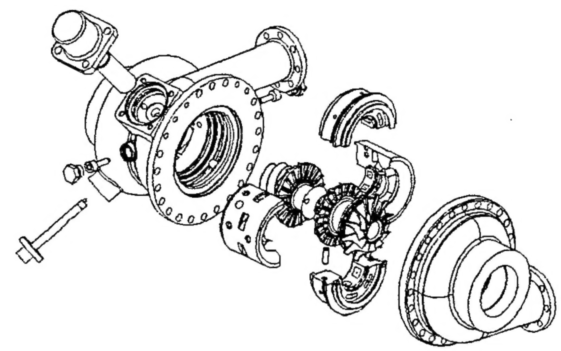


Figure 3. Low parts count simplifies assembly

ALH/E08-A TEST FACILITY MATH MODEL

An ALH/E08-A test facility system math model was created based on the models developed for testing of the SSME Alternate Turbopumps at E08 test stand starting in 1990. The highly integrated model utilizes thermodynamic and fluid mechanics representation of key test stand components combined with ALH pump, turbine and axial load characteristics and properties of fluids.

The transient model has the ability to run at both design point and off-design operation. This math model is used to establish start, power level ramps, steady state and shutdown sequencing procedures which in turn is used to establish test run programs. The model is also used to define test facility valve requirements, plumbing design and facility modification impacts; support test planning and pre-run predictions; define control methodology; and to maintain operation within all operability constraints. Operability considerations include:

- Avoid pump cavitation, stall and overspeed caused by rapid flow acceleration, low inlet pressure and violation of suction performance.
- Minimize water hammer.
- Turbopump performance parameters.
- Avoid excessive turbopump axial load unbalance.
- Abort criteria and accommodation

Fluid properties are provided by a NIST (formerly NBS) database. The ALH/E08-A test facility model simulates:

- Volume dynamics;
- Pump inlet and discharge line inertia;
- Plumbing line losses;
- Design and off-design turbine and polytropic pump characteristics;
- Turbopump axial loads;
- Valve characteristics; and
- Proportional plus integral controller with a digital to analog interface, second order actuator dynamics, sensor dynamics and open or closed loop capability.

The model was calibrated using a series of cold flows tests (see Validation and Calibration section) and from post ALH test data analysis.

TEST FACILITY

Pratt & Whitney's E08 test facility was selected for testing the ALH turbopump. The test team using data from the critical design review, pump and turbine maps, ALH/facility analytical model, and a risk analysis of the facility and test article established facility requirements. The requirements were:

- Facility mechanical system to accommodate all turbopump flows and temperatures from 0-100% RPL and Q/N excursions of +/- 20%.
- Data recording capability to record all facility and test article parameters at 100 data scans per second and selected parameters at up to 80,000 scans per second.
- Control system to provide open loop control of the pump discharge, turbine exit, and turbine inlet valves as well as the capability to close loop control turbine inlet pressure to the turbine inlet valve.
- Test article interface loads not to exceed 2000 lb (907 kg) in the X, Y, and Z directions or 2000 in lb (2304 cm kg) moment in any direction.

Description

Construction of the mechanical, electrical, and control systems was performed over a 6-month time frame. The test facilities, designated E08-A, mechanical systems consisted of four primary subsystems including the pump inlet, pump discharge, turbine inlet, and turbine exit.

LH2 System

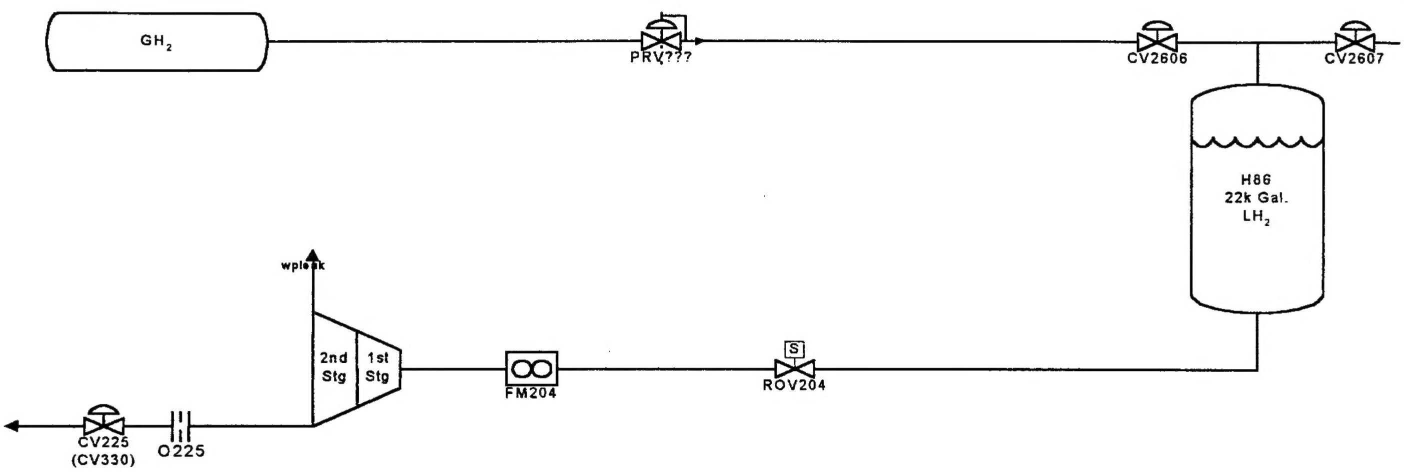


Figure 4. ALH LH2 Supply/Discharge System

The pump inlet system was designed to have the ability to supply 0-16 pps (0-7.3 kg/s) of LH2 at 0-250 psia (0-17.6 kg/cm^2), 37-42 R, supplied from the existing test stand's 22,000 gallon (83.3 m^3) cryogenic tank. This system utilized existing plumbing upstream of the shutoff valve (ROV 204, see figure 4) built during SSME-ATD testing in the early 1990's and new hardware downstream of ROV204 which was purchased under USAF contract F04611-97-C-0029.

The pump discharge mechanical system was also designed to have the ability to flow 0-16 pps (0-7.3 kg/s) of LH2 at pressures from 0-4600 (0-323.4 kg/cm^2) psia. A control valve (CV225) was used for open loop, back pressure control and was followed by a secondary flow measuring orifice. The single vent in the discharge system was used to vent trapped GH2 at the high point to prevent rotor rotation with unpressurized hydrostatic bearings. Discharged LH2 was routed to the existing E08 flare stacks.

GH2 System

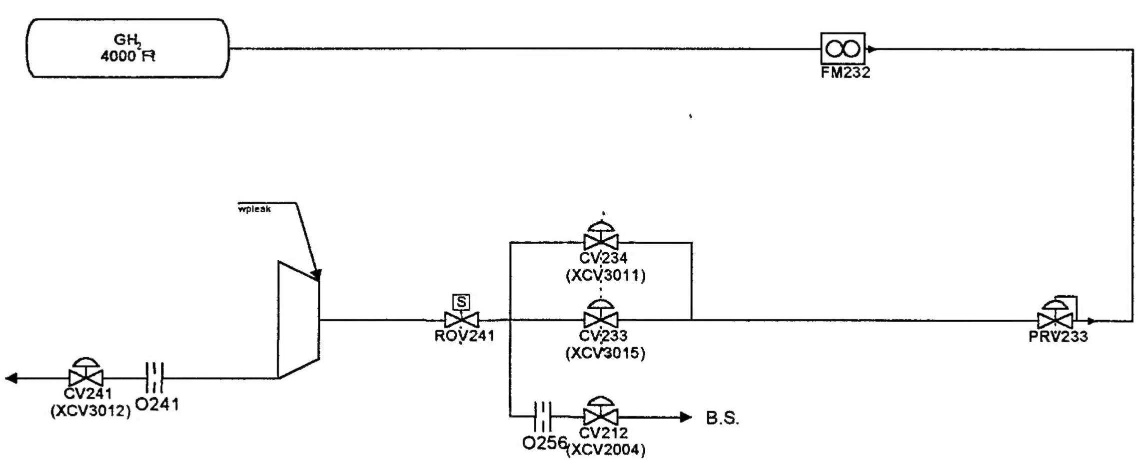


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Figure 5. ALH GH2 Supply/Discharge System

Gaseous hydrogen (see Figure 5) was supplied from six high-pressure bottles containing 4050 wcf (115 m^3) of ambient gas at 7200 psia (506 kg/cm^2). A trade study was undertaken and concluded that for control system stability and increased run time, a pressure regulator would be used to regulate the pressure supplied to the control valves down to 4300 psia (302 kg/cm^2). This decision allowed run times to reach the 70-second range without decreasing control system stability. However, a vernier control valve (CV234) was also included as a back up to the pressure regulator. A variable area GH2 dump (CV212) incorporated into the turbine supply system provides a controlled method of setting the turbine start flow. The GH2 supply safety systems included a rupture disk set to 5500 psia (387 kg/cm^2) and a relief valve set to 4500 psia (316 kg/cm^2). Downstream of the control valves, a fast acting, pneumatic valve (ROV241) was used as the rig safety shutoff valve.

The turbine discharge system was designed with the ability to flow 0-16 pps (0-7.3 kg/s) of GH2 at 0-1600 psia (0-112 kg/cm^2). It incorporated an open loop control backpressure valve (CV241) and a secondary flow measurement orifice. Discharged gas was routed to a different burn stack than the liquid system used.

Instrumentation

Data recording was performed using both test stand instrumentation and test article instrumentation. Facility instrumentation for E08-A consisted of temperature, pressure, and flow measuring devices. Turbopump instrumentation included internal pressure measurements, external housing temperature measurements, external accelerometers, and two proximity probes to measure rotor position and speed. Redundant sensors were added for parameters deemed critical to turbopump health and test program objectives. All parameters were recorded on a high speed, digital data system at 100 scans per second (sps). Selected headers were recorded at 20,000 sps digitally and on the analog FM tape system, which has the capability to be digitized at up to 80,000 sps. Figure 6 details the pump internal pressure instrumentation.

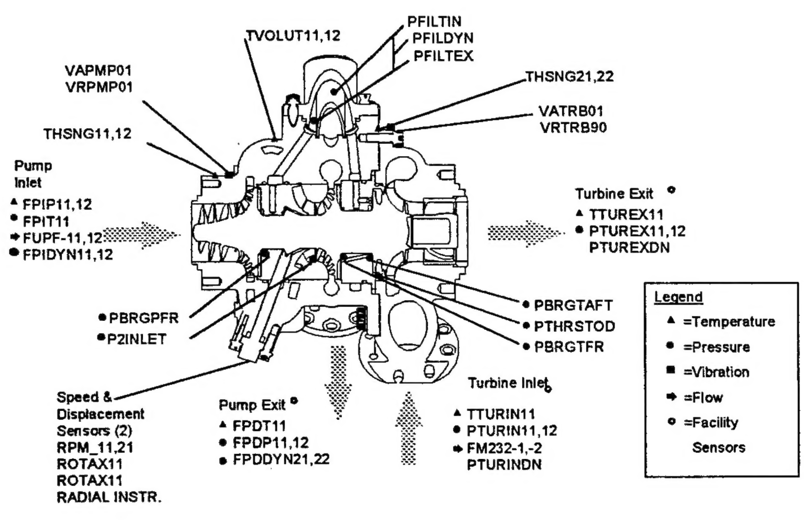

Figure 6 ALH Test Article Instrumentation

Validation and Calibration

The component test facility (E08-A) system was validated and calibrated prior to the ALH spin tests using separate GH_2 and LH_2 cold flows. The LH_2 system for the pump side cooldown, supply and discharge system, and the GH_2 turbine supply and discharge system were validated and calibrated prior to installation of the ALH turbopump by using a turbopump simulator to connect the supply and discharge lines. The data from these tests was used to calibrate the ALH/facility simulation model which in turn was used to establish run programs to test the ALH.

The LH_2 purge systems were exercised to determine minimum flow rates needed to purge the lines; therefore, reducing the possibility of rotating the ALH during purging. Plumbing and simulated ALH cooldown procedures were developed which included the required LH_2 supply tank pressure and the plumbing's high point bleed affect on cooldown flows while assuring low flows through the LH_2 system; therefore reducing the possibility of spinning the rotor. After the plumbing was chilled to operating temperatures, the supply tank was pressurized to its starting pressure to evaluate its operation and response. A simulated ALH start, stepping the pump discharge valve (CV225) to its start position, initiated the calibration of the LH_2 system. The pump discharge valve (pump flow) was calibrated by 5% position increments up to and down from (hysteresis affects) its maximum opened position, which is mechanically fixed to reduce pump overflow events. This resulted in an effective area versus position curve for the ALH/facility simulation model. While flowing the LH_2 system, the flow meter and the pump discharge orifice were calibrated. The pretest cold flow shutdown was a planned abort to evaluate the response of the valves in the LH_2 system and ensure the safety of the hardware in the event of an unexpected problem requiring premature test termination.

The GH_2 purge systems were also exercised to determine minimum flow rates needed to purge the lines, again to reduce the possibility of rotating the ALH during purging. The ALH test philosophy was to establish a constant pressure upstream of the turbine inlet valve (CV233) and to use it with the turbine discharge valve (CV241) to control the turbine pressure and flow rate. The pressure regulator system (PRV233) was checked to determine it's response and accuracy. Again, a simulated ALH start, stepping both the turbine inlet and discharge valves to their starting positions at the appropriate times initiated the calibration of the GH_2 system. Both the turbine inlet and discharge valves were calibrated by 10% position increments, resulting in an effective area versus position curves for the ALH/facility simulation model. While flowing the GH_2 system the flow meter and turbine discharge orifice were calibrated. Closed loop control of the turbine inlet pressure at 5 seconds, using the turbine inlet valve, was also verified and Figure 7 shows the requested and actual pressures for the checkout test. Shutdown was a planned abort to evaluate the response of the valves in the GH_2 system.

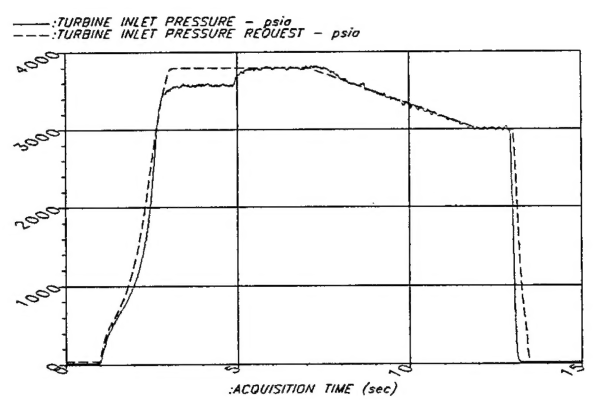

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Figure 7 Closed Loop Control of Turbine Inlet Pressure

TEST

Cooldown

The ALH/facility cooldown philosophy was to chill the pump side system to LH_2 temperatures, eliminate all gas in the pump, its supply, and discharge lines without cooling the turbine, while ensuring little or no rotation of the rotor. This was performed by setting the LH_2 supply tank at low pressure and chilling down the pump upstream plumbing while dumping LH_2 upstream of the pump. Also, bleed valves in the high points of the LH_2 system upstream of the pump were systematically opened and closed to eliminate gas. When the plumbing upstream of the pump was sufficiently chilled, the pump discharge valve and a downstream bleed valve were also systematically opened and closed to chill down the pump and the rest

of the LH_2 system. Once the LH_2 system was chilled down, all LH_2 valves were systematically opened and closed to maintain a ready to test LH_2 system. There is a leak path from the pump (thrust bearing) to the turbine and as cold H_2 leaked into the turbine it would gasify and pressurize the turbine side to match the pump side pressure. This kept the turbine relatively warm and also tended to balance the axial thrust loads. Figure 8 shows the ready to test ALH on the E08-A stand.

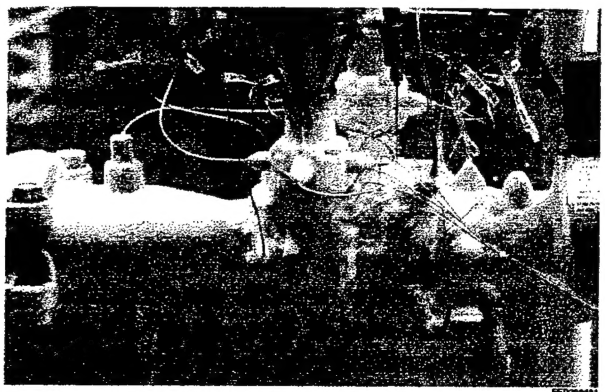

Figure 8 ALH Ready for Test

Transients

The ALH start transient philosophy was to quickly ramp the turbopump to a low power setting at design point Q/N to decrease the time duration of radial and axial rubs. Figure 12 shows both the turbine side inductance probe and the pump side capacitance probe rotor speed during the start transient (up to ~ 97K RPM). rpm The inductance probe speed dip is erroneous data possibly caused by a rotor shift. Turbine total pressure ratio and flow rate and pump delta pressure rise and flow rate during an ALH start are shown in Figure 13. The ALH is designed so that the axial thrust loads from the turbine and pump section (once it starts pumping) are offset by the thrust bearing. The thrust bearing is between the 2nd stage impeller and the turbine. The thrust bearing's axial thrust balancing capability is a direct function of pump discharge pressure. Therefore, it is important to get to a significant pump discharge pressure quickly to increase the bearing's axial thrust balancing capability to reduce axial rubbing. Figure 12 also shows the predicted axial rub load during an ALH start. The hydrostatic bearing's are also fed by the pump discharge pressure and their effectiveness is a function of the delta pressure across the bearings. Therefore, higher feed pressure would mean a stiffer bearing and less chance of radial rub.

The low power level speed was based on acceptability to the rotordynamics and structures disciplines. The major rotordynamic concerns were turbine blade and pump impeller modes. The major structural concern was over speed. Because of these concerns, the low power speed setting was well below the design speed so there was significant overspeed margin.

As with the start transient philosophy, the shutdown (S/D) philosophy was to decel the rotor as quickly as possible from a low power setting to decrease the time of radial and axial rubs. Figure 14 shows the rotor speed and predicted axial rub load during an ALH shutdown. The capacitance probe speed spikes are erroneous data. Figure 15 shows the turbine and pump parameters during an ALH shutdown.

Steady State

The predicted axial travel of the rotor during steady state operation is approximately 0.006 inches (0.0152 cm). This rotor travel affects the thrust bearing axial loads which is used to offset the turbine and pump axial loads. The test facility pump discharge and turbine inlet and discharge valves were set so that axial loads during steady-state operation would be balanced with the rotor centered; therefore, no axial rubbing. Test data analysis indicated no axial rubbing during steady-state operation.

Figure 9 shows a comparison of component test data with predicted pump performance. During steady-state operation, the pump reached a speed of 97,000 rpm and a discharge pressure of 1450 psi (102 kg/cm^2) at a flowrate of 1,000 gpm (3.8 m^3/min). Although it should be noted that the prediction is for higher operating speed, which would be expected to result in a different impeller tip clearance, the data shows very good agreement with predictions.

Figures 10 and 11 show a comparison of component test data with predicted turbine performance. During steady-state operation, the turbine flow parameter was 2.45 at a total pressure ratio of 1.85. The turbine data also shows very good agreement with predictions.

Post test data is used to update and calibrate the ALH/facility simulation model.

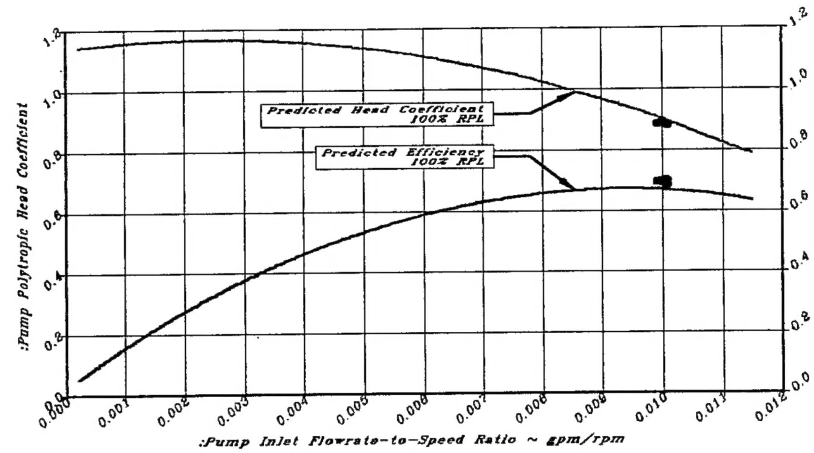

Figure 9 Pump Performance

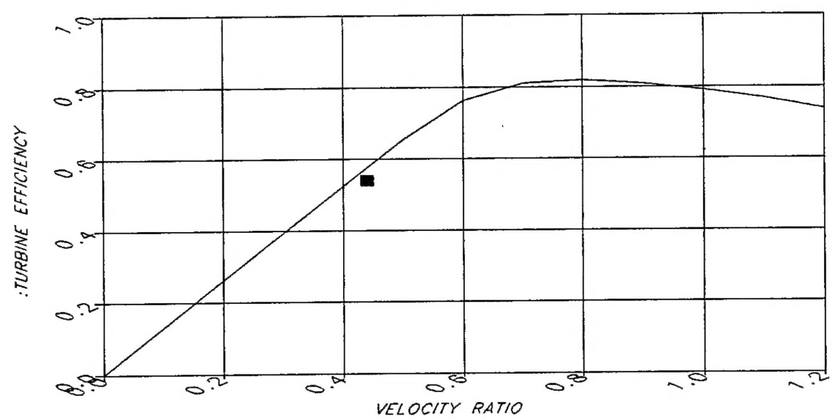

Figure 10 Turbine Efficiency vs. Velocity Ratio

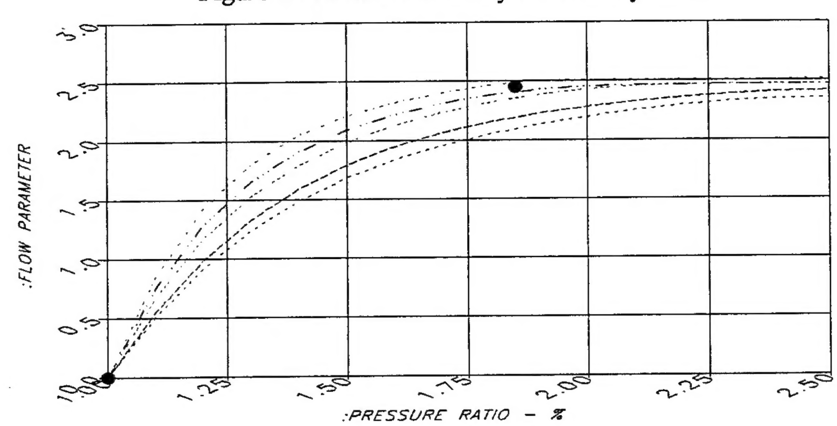

Figure 11 Turbine Flow Parameter vs. Pressure Ratio

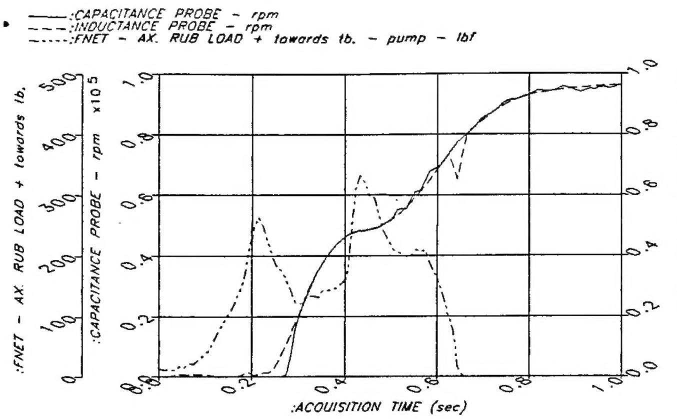

Figure 12 Rub Loads and Speed During Start

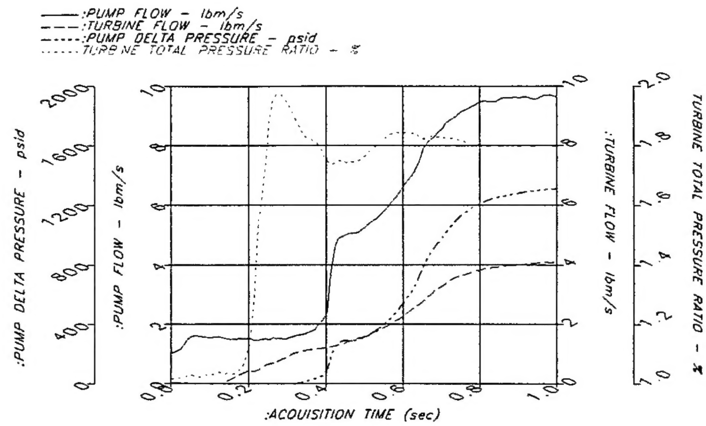

Figure 13 Turbine and Pump Performance During Start

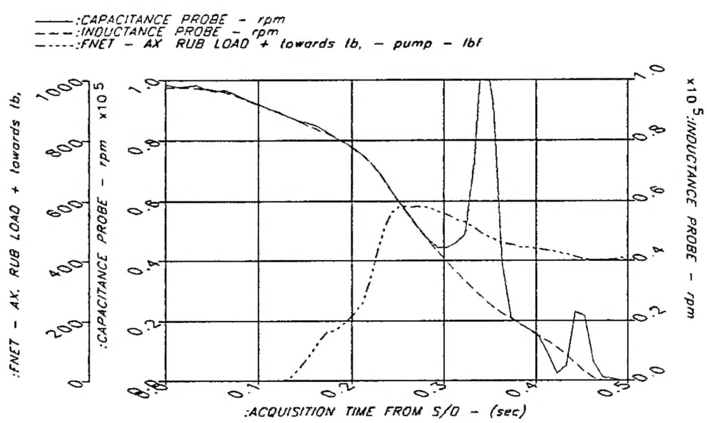

Figure 14 Rub Loads and Speed During Shutdown

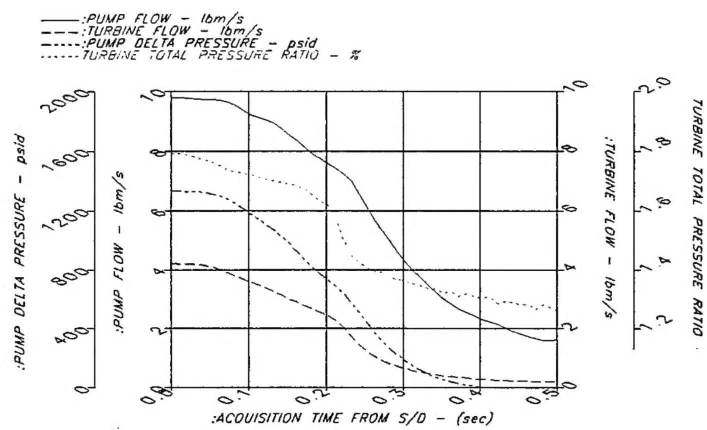

Figure 15 Turbine and Pump Performance During Shutdown

SUMMARY//CONCLUSIONS

The ALH turbopump was assembled and disassembled in a small fraction of the time it takes either an SSME or RL-10 turbopump. This demonstrated ability to turnaround the hardware fully validated both the design philosophy, to keep the parts count low, and the design process, to take assembly and manufacturing into account for the baseline design. A calibrated E08-A test facility combined with the ALH test component simulation model resulted in successful testing. The ALH transients and the steady-state turbine and pump performance matched pretest predictions showing both the benefit of the integrated test facility modeling and that this design can deliver the low weight, low cost, high power density and high efficiency needed for an advanced expander engine.

LESSONS LEARNED

In a turbopump, which has no roller element bearings and relies on hydrostatic support, a through understanding of transient rubs both radially and axially, is critical to the operation of the pump. To keep component test axial rubs within expected engine levels an integrated, transient axial load analysis tool is needed. Also, instrumentation that can indicate when axial rub occurs and where the rotor is positioned as well as appropriately placed pressure data is helpful for model calibration. The bearing system should include significant margin for rubs. The torque reaction of the rub contact areas must be included in the transient analysis for both start and S/D. These considerations can significantly affect the hardware configuration and choice of materials and as such, must be addressed as early in the design process as possible.

THOROUGH

NOT

WITH

ACKNOWLEDGEMENTS

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